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EVOLUTION OF VALUE ENGINEERING TO AUTOMATE INVENTION IN COMPLEX TECHNOLOGICAL SYSTEMS

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Abstract. Many global companies specialising in complex technological systems use forms of group decision making to select a combination of solutions from suppliers. This requires technical expertise and up to date awareness of what is available within and outside the company. The use of Artificial Intelligence (AI) seems like an obvious progression but is fraught with difficulties. As a step in this longer-term direction, this paper looks to a methodology that uses the idea of functionality to first list abstract requirements before finding potential solutions with appropriate performance characteristics. This paper re-examines a methodology called Value Engineering (VE) which mixes measurable and immeasurable concepts in its foundational idea. This paper reasons and deduces a new way to conceive this foundational idea so that it can be modelled mathematically and provide a useful step towards a database ontology and schema that would suit AI. It also provides an immediate benefit to VE practitioners in workshops.

Keywords: AI, value engineering, function, functionality, invention, innovation

1. Introduction

This paper combines many years of industrial experience, understandings drawn from literature reviews and a model which is reasoned. The purpose of the paper is to mark a starting point for further research built out of practice. It does this by developing a new method that will improve dialogue between manufacturers and customers. The paper has two aims. A longer-term aim that opens a way for Artificial Intelligence (AI) to be used and a short-term aim to produce a way that Value Engineering (VE) can better utilise co-creation.

Whilst VE practice is still firmly rooted in the idea of group decision making and workshops, its foundational ideas hold the key to coordinating many aspects of an innovation management process in large technological systems. The successes of VE stood on the articulation of functionality in multi-disciplinary teams within workshops (Kaufman, 1985) and this paper offers a new methodology that can help practice.

This paper distinguishes the act of invention from the implementation of inventions which is viewed as innovation (Tidd and Bessant, 2015). It will focus on invention and limit its scope to the production of credible ideas from experts that have yet to stand the test of adoption.

What characterises the complex technological systems this paper focuses on is they integrate many component-solutions made by suppliers. Often there are so many possible options and combinations that it can overwhelm a team of multi-disciplinary decision makers, especially as workshops are time constrained. Examples of a component-solution made by suppliers could be high speed railways (Berawi et al, 2015) railway operation and maintenance (Rahman et al, 2018), a plan for a smart city (Woodhead, 2018), an airport (Yuliawati et al, 2015). They eventually become choices requiring expert technical selection in some methodological framework.

2. What is VE and why is it worth considering?

This paper begins by critiquing VE (SAVE International, 2020a, 2020b) to rework this old invention methodology and build new theoretical foundations that enable new modes of practice. Based on industrial experience, the authors have seen large global corporations buy new equipment that they already owned but did not realise, because idiosyncratic naming did not link to needed functionality. For example, a former client, a leading global engineering firm in the UK, spent £5 million building a test rig when they already had one in the USA that could do the same work. Similar situations for global companies were observed in practice and often due to inconsistent naming conventions across many countries.

A common factor facing large companies seems to be a metadata problem and how 'things' are inconsistently named in databases. A thing's name and how it can be useful in a particular context is not always obvious. To give a concrete example think of a chair being used to prop a door open. The chair was not designed for this use, but humans often see other properties in a thing that they can make use of in inventive ways. It is unlikely a description of a chair in a database would convey these additional properties and so an algorithm searching a database would likely miss this possibility.

To make progress this paper will focus on what is often seen as the distinguishing aspect of VE through a reworking of an old idea of Function Analysis (Miles, 1962, Bytheway, 2005, Kaufman and Woodhead, 2006) that links to a view of a relationship between value, function and cost first put forward by Miles (1962).

i) Value = Function / Cost

Miles (1962) in his first edition talked of a process that could span several weeks with internal engineers working on ways to do what was already done, faster, better, cheaper. Interestingly this was not part of his second edition, probably because a 5-day workshop model had been established as the dominant delivery model by then (Miles, 1972; King, 2000).

At the heart of this initial version of VE (Miles 1962) was a period of intense study amongst a team, typically engineers. This deeper enquiry as a group is a root cause of valuable multi-disciplinary team learning and successes in early VE. However, what once took weeks is typically done in days now, some episodes in the UK Construction Industry not even taking a single day. This is a mistaken separation of the performance of a methodology from the act of meaningful team learning and development of penetrative insights.

However, VE as a practice has not really evolved its core theories to play a much more central role in digital innovation as it clings to an interventionist model in capital project lifecycles at stage gates. In the oil industry a number of interventionist approaches at stage gates are also mandated such as 'constructability studies' and collectively named "Value Improving Practices" (McCuish, 2002; Hermanides, et al. 2010). What is needed is a return to Miles' original views that focused on team-based invention outside of processual time constrained workshops.

3. The core idea in VE

The seminal idea of Larry Miles (Miles, 1962) was "Value = Function / Cost" but this was later changed to Function / Resources. Even so, this adaptation has the same issues as its original form in that it mixes measurable (e.g. cost)and immeasurable (i.e. function) concepts.

By understanding that the function of a human heart is to 'pump blood', this naming enables the consideration of other mechanisms that can perform this function should the human heart fail, but to measure the heart's value is not easy. This paper adopts a pragmatic-realist perspective

(Rescher, 1999) and so does not dismiss immeasurable concepts as would other philosophical stances. This does require more precision in what is meant when using the word, "function".

4. What is meant by function and functionality?

For Miles (ibid), "All cost is for function". He built a logic which basically says customers buy 'things' because they 'do something the customer desires' be that a mode of usefulness or a form of aesthetic beauty that causes delight.

When identifying a function within the practice of VE, Miles explained how it took effort to peer through our superficial notions of things and ask, "what does it do?". Miles (1989, p25) explains, it takes,

> "Intense concentration, even what appears to be overconcentration of mental work on these functions, forms the basis for unexpected steps of advancement of value in the product or service."

For Miles and many practitioners, and there are many that could be cited (e.g., Crum, 1971; Dell' Isola, 1982; Kelly and Male, 1991; Kaufman and Woodhead, 2006 etc), the idea of function in VE is about some kind of 'action' performed on some 'thing' and this becomes the 'requirement' requiring a 'solution'.

The required action is often named by a verb and the target of that action with a noun in a syntactical process that is intended to make people think more deeply and clearly about what exactly something does. However, in practice this can lead to a focus on syntax rather than functionality (Woodhead, Kaufman and Berawi, 2004).

What clearly distinguishes VE from other innovation methodologies is this identification of functionality and the consideration of 'other ways' to perform that functionality. This exploration of functionality attempts to look deeper than any superficial first impression to articulate a purpose, *raison d'etre*, and the operational contribution a part makes to the whole system it is within. This offers a way to link requirements to solution selection as in figure one.

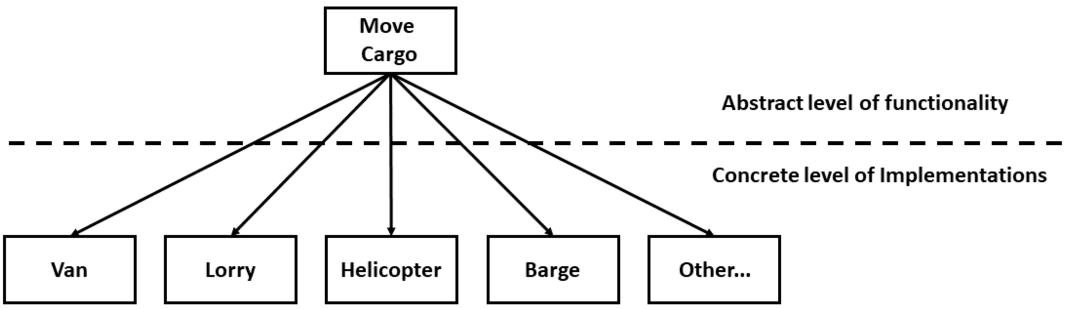


Figure 1. Abstract function and multiple ways to implement it

Figure one shows a simplistic example of a single needed function and multiple ways that could be chosen to perform that functionality. The key idea is the ability to separate the required intentionality from a list of concrete implementations so the 'best' one could be selected. The actual selection of what counts as 'best' would be based on attributes such as time, cost, quality, carbon footprint and so on, in a specific context and from the perspective of a buyer.

For this paper, the context is some kind of technological ecosystem which comprises functionality to be performed and technology to perform it. This begs the question, what is meant by technology and why is that relevant to this discussion?

5. What is Technology and how does it link to Functionality?

The philosopher Ferré, (1995) argued that technology is the 'practical implementation of intelligence'. This implies technology is more than the device itself which comprises inanimate objects that operate to a design in order to create a form of usefulness or aesthetic. Consideration of Heidegger's (2001) view of technology reveals it is about bringing something into existence. The act of conceiving the needed functionality and then inventing a way to perform it conceptually unifies as 'technology' manifests. Searle (1995) argues something similar from the perspective of social constructivism when he explained a coin can function as money and also as a screwdriver used to twist a screw out of wood for example. The idea of functionality is independent of the solution used to perform it. First comes the required functionality then comes the search for a way to perform that required functionality. Feenberg (2012) explores a number of perspectives of the relation between our socially determined idea of functions in devices and a natural causality that allows those devices to work. He also points out that from a philosophy of technology perspective, this turns out to be a complicated discussion and not all eminent philosophers in the field agree. Kroes (1998, 2009), another philosopher of technology, offers an epistemological and ontological view of functionality as part of physical structures. He saw the abstract idea of functionality but does not separate it from the idea of the real thing that possesses it. Seni (2005) on the other hand, held an epistemological view that could separate these two ideas. Our view is closer to the epistemological view of Seni that accepts the conceptual separation of functionality from ontological artefacts as key to invention in complex technological systems.

A problem in practice is a confusion as to whether functions, actions, or processes (Mahner and Bunge,2001) are being considered, especially in time constrained workshops. Berawi (2006) created a thought process that separated functions from real world actions or processes. For him, the sense of functionality is about an essential contribution to a system of other functions that collectively interoperate, such as the bodily function of a heart within the human body. This links the idea of function to an idea of effectiveness and purpose and provides a useful heuristic to select named functions to use as labels in the training of a neural network.

Functionality is a way of recognising what a thing can do, such as using a chair to prop open a door. So functions are epistemological insights into how ontological properties could be used in a method to achieve a desired outcome. As such, they are abstract requirements for empirical technologies.

6. The Role of Solution Attributes and Properties

Our longer-term idea is that if the attributes (i.e. features) of each potential solution to a key function (e.g. move cargo) were known *a priori* then they could be stored in a database and selected by an AI algorithm to find the best choice from all options within a global enterprise. The user would simply enter performance characteristics for a function and AI will find the best fit of options stored within its database. The AI would be a type of 'recommendation system', and a google search shows numerous tutorials.

During experiments with Machine Learning (ML) a key issue was scarcity of data for a single function to train on, and so the Gaussian Naive Bayes classifier proved to be the best option. With more data we expect different classifiers to outperform our initial findings.

The articulation of theories of functionality and the generation and selection of solutions to perform that functionality are typically done in a workshop environment in VE practice. These are usually multi-disciplinary workshops. The building of functionality models, known in VE as "FAST diagrams", have more relevance to those in the workshop as a process where different disciplines gain shared insights into the way other disciplines see how things need to work in a complex technological system. The authors have access to the outputs of some historical workshops and are positive about our next steps towards using AI but also wary of how complex this challenge will be.

In workshops considering a common challenge, such as the design of an oil pipeline, the outputs can be dissimilar suggesting the act of conceptualisation depends on the knowledge held in the heads of workshop participants. AI offers the potential to perform better by allowing forms of open innovation (Chesbrough, 2003), and knowledge not in the minds of participants, to be part of the invention process. This is seen as a worthy longer-term goal but accept this grand vision is far from our capability today.

This paper will now put aside a longer-term AI ambition and focus on overcoming the tendency of VE and the use of functionality to singularly head towards cost reduction. As above, a key issue is both the idea of value and needed functionality are subjectively identified by at least two key stakeholders. There is the producer who seeks the highest price for their wares and there is the buyer seeking to pay the minimum for them.

The actual price arrived at must be when both of these two stakeholders believe the number being quoted for the price is at an optimal point. It is viewed as a fair price by the producer for the effort of bringing their solution to the market. It is likewise viewed as a fair price given its opportunity cost by the buyer. The challenge is to create a workshop process that would enable this point to be found in a co-creation mode (Ranjan, and Read,2019).

7. Theoretical Framework

The abstract concept of functionality allows a conceptualisation that separates a pursuit of effectiveness (i.e. worthy goal achievement) and efficiency (i.e. optimal method).

Figure one showed an example of a named function and that multiple options existed to perform that function. As was explained, the choice of a specific solution is context dependent and value laden as it would compare cost, timeliness, security and so on from a particular perspective with vested interests.

VE holds a key to automated invention with AI because it yields an explanation of how to solve complex technological problems by identifying needed functionality then considering different ways to perform that functionality. But first its main criticism, that it only focuses on cost minimisation, must be overcome so its possibility can be seen.

8. Methodology

This paper relies on reasoning, deductions and social constructivism that combines insights from literature and over 30 years of experience of stimulating inventions and innovation in corporations and large capital projects. This has been pursued in an action science (Argyris, 1995; Kaplan, 1998, McNiff, 2017) approach grounded in practice that sees the whole idea of scaling inventions to become innovations as an act of organisational learning (Van de Ven, et al., 2008). It builds on this prior knowledge in order to deductively reason a new method that will help today's workshop-based practice as well as provide a starting point for an AI method later.

As previously explained, current VE practice tends to place an emphasis on efficiency, and this is in part because its core formula can only measure cost and so assumes value and functionality. Here is the theoretical basis for change:

i. Functionality is a concept of required work to be done (i.e. a form of requirement)
ii. The way functionality is achieved is through the performance of measurable solutions.
iii. Measurable solutions can impact value in a context differently (e.g. one method more expensive than another)
iv. Effectiveness is a view based on the adequacy of named functionality to achieve a predefined desirable aim or outcome.
v. Efficiency is a view based on the cost of a solution and its translation into a price that customers would be willing to pay

The question becomes, how can Miles' original idea (i.e. value = function / cost) be reworked to better handle the calculus between effectiveness and efficiency?

8.1 Reworking the Numerator of Function to become Functional Value

For the numerator "Function" this paper proposes changing this to "Functional Value". This is done to reflect the manufacturer or producer identifies functions in the act of design. However, the manufacturer holds the assumption that all functions are necessary or why would they include them? Customers need to test this assumption so an idea of what the manufacturer believes is valuable can be compared to what customers think is valuable. This co-creative tension opens doors to numerous new approaches to designer and stakeholder dialogue.

For ease of explanation, imagine just four functions (See Figure two), have been identified by the designers that they believe the customer, in this case a food kitchen for homeless people, will desire and are necessary to make a system of all 4 functions work in an integrated fashion as a product or service.

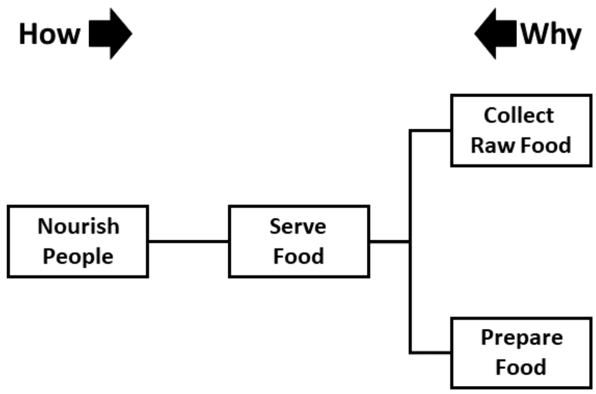


Figure 2. A System of Functions Representing the Idea of Functionality

Figure two makes explicit, 'what has to be done' without specifying 'how it is to be done'. If there were 4 functions offered by the producer then the same number of tokens could be allocated to customers that would pay for a solution. If the manufacturer's designers view of necessary functions is valid, then in theory, each customer will place one and only one token on each function (i.e. share them out evenly). However, if customers prefer one function more than another and allocate say 2 tokens to that function, then at least one function will show as not being valued. This is why the number of tokens given must be the same as the number of functions the design team believe are needed, so a gap may appear.

If a function gets zero tokens then the design team should try to innovate their solution so that there is zero cost allocated to the delivery of the function customers do not care about. It becomes a tool that allows designers and customers to use notions of value to shape the act of co-creation by calculating functional value.

This idea will be explored further. Imagine there are four different functionality models, each comprising 4 functions only. Figure two shows one for a food kitchen to nourish people and now a further three additional cases are proposed for different problems such as how to reduce carbon emissions, how lift people out of poverty, how to rethink universities and so on.

For each of the functionality models five customers are asked, people that have or are highly likely to consume the product or service, to allocate 4 tokens each. In theory each customer will spread their four tokens over the four functions equally as they are supposedly all necessary for the consumer in the eyes of the designer. This is shown in the first matrix below (see figure three). This is what the producer expected and so all 20 cells (i.e., 4 functions x 5 customers) have a value in them out of 20 possible cells, yielding a Functional value of 100% (i.e., 20/20 = 100%)

Matrix 1: 100%

Customer \ Function	A	B	C	D
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1

Matrix 2: 40%

Customer \ Function	A	B	C	D
1	0	2	1	1
2	0	0	4	0
3	0	0	0	4
4	0	0	1	3
5	0	0	4	0

Matrix 3: 25%

Customer \ Function	A	B	C	D
1	0	4	0	0
2	0	4	0	0
3	0	4	0	0
4	0	4	0	0
5	0	4	0	0

Matrix 4: 0%

Customer \ Function	A	B	C	D
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0

Figure 3. Only four functions considered by five customers

In the second matrix (see figure three), customers allocate tokens in different ways. This would tell the producer that there needs to be a deeper enquiry to understand why this inconsistent voting is happening. Customers might belong to different segments that are not understood. In matrix 2 (see figure three), eight cells have numbers in them out of 20 yielding a Functional value of 40% (i.e. 8/20 = 40%).

In matrix 3 (see figure three), customers converge to agree function B is the only one that is valuable to them, and place all four tokens on B. The designers must now try to ensure minimal cost in delivering functions A, C and D as customers do not value them, whilst also striving to enhance function B. This matrix has 5 cells with values in them out of a total of 20 and so yields a Functional value of 25% (5/20 = 25%). Out of 20 possible tokens, customers do not see value in 15 of them.

Finally, matrix 4 (see figure three) shows a potential failure for the manufacturer's design where customers say all functions have zero value for them.

This paper has now explained a method to calculate a value for the numerator and which can be used to simultaneously explore ways to increase or decrease value from both producer and customer perspectives.

We can now show our numerator as:

ii) 0% <= Functional Value <= 100%

8.2. Reworking the Denominator to become the Probability of a Price

The next challenge is to calculate a denominator that scales with the numerator. Price is chosen as the denominator rather than cost as it better aligns with the customer's view of value. This subtle change is important. As stated previously, Miles seminal ideas formed in an era of material shortages and where corporations had more economic power than consumers, as demand outstripped supply in post-World War II (Goodman, 1995; pp37-39), so focused more on their own internal efficiencies. Today, the opposite is the case and fickle customers with internet enabled market intelligence can find rival products much more easily than in Miles' time (Hilton, 2007, Labrecque et al, 2013).

The numerator is a percentage between 0% and 100%. The denominator needs to be the same scale so a ratio can be constructed that allows functionality and predicted price to work together to give some indication of value.

To achieve a denominator that is also a percentage which allows an association between the design price and rival offerings in the market, the Student T distribution will be used to find the cumulative probability of a price from a distribution of comparable prices for similar purchases of products or services or for shadow products or services.

Imagine, from an internet search on a platform such as eBay or Alibaba, that a product or service similar to what is being innovated has the following prices (e.g. $ AUD) that will set customer expectations: { $24.50, $26.20, $28.60, $29.70 }.

The mean is $27.25, and the standard deviation is $2.34. The number (n) in the sample is 4 and so $\sqrt{n} = 2$. From this the standard error is $2.34/2 = 1.17

The t score of interest is the price of our solution minus the mean price and then divided by the standard error. Say our solution is currently priced at $26.0 then ($26.0 - $27.25)/ 1.17 gives a t score of -1.068.

The Cumulative Distribution Function (CDF) can be used to find the probability of the t score within a range from very cheap (i.e., 0%) to very expensive (i.e., 100%), for our price. What is of interest is the probability of our price point which enables consideration of the likelihood it would be acceptable to customers based on proximity to the mean price and customer expectations of functionality.

In Microsoft Excel the built-in function used is *T.DIST(t score,(n -1),TRUE)* for this task. The bracket with n-1 is for the degrees of freedom. For our example the input would be *T.DIST(-1.066,3,TRUE) = 18.22%*

If a decision to price our product or service at exactly the mean price of $27.25 then the CDF would have been 50%. This example shows that the planned price is on the low side of what customers might be expecting. This approach demonstrates a way to show the probability of price as the denominator.

8.3. The New Theory of Modelling Value, Functionality, and Price

This paper outlines an approach to model in a way that provides a logical consistency within a single decision space. To avoid confusing different definitions of value, the dependent variable will be named the "Value Ratio". From matrix 2 above (see figure three) the numerator is 40% and moving away from the perspective of cost to price (i.e., cost plus mark-up) a customer will pay, the current price of $26.00 has a cumulative probability of 18.22% of being expected.

The Value Ratio (VR) in this example is 40% / 18.22% = 219.54%

If the manufacturer's designers now select alternative methods to perform the same functionality, then they will arrive at a new cost (say $27,25 which translates to 50% probability of being expected by customers) then this yields a Value Ratio of 80% (i.e., VR = 40%/50% = 80%). They will see this second option has less value than the previous option: 219.54% v 80.00% and be able to objectively disregard it as inferior.

What is more, all possible outcomes can be mapped by considering the ratio of all possible functional values from 0% to 100% over the cumulative probability of price from 0% to 100% (see Figure four), which is shown in Table 1.

Cumulative probability of price											
100%	1.0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
90%	1.1%	11%	22%	33%	44%	56%	67%	78%	89%	100%	111%
80%	1.3%	13%	25%	38%	50%	63%	75%	88%	100%	113%	125%
70%	1.4%	14%	29%	43%	57%	71%	86%	100%	114%	129%	143%
60%	1.7%	17%	33%	50%	67%	83%	100%	117%	133%	150%	167%
50%	2.0%	20%	40%	60%	80%	100%	120%	140%	160%	180%	200%
40%	2.5%	25%	50%	75%	100%	125%	150%	175%	200%	225%	250%
30%	3.3%	33%	67%	100%	133%	167%	200%	233%	267%	300%	333%
20%	5.0%	50%	100%	150%	200%	250%	300%	350%	400%	450%	500%
10%	10.0%	100%	200%	300%	400%	500%	600%	700%	800%	900%	1000%
1%	100.0%	1000%	2000%	3000%	4000%	5000%	6000%	7000%	8000%	9000%	10000%
	1%	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**

Functional value

Table 1: Value produced from a ratio of Functional value to probability of price.

In table one, if the functional value is held constant (e.g., 40%) then consideration of different probable prices looking from bottom (1% cumulative probability of price) to top (100% cumulative probability of price), a trend can be observed as the prices rise for the same functionality then value decreases from 4000% to 40%.

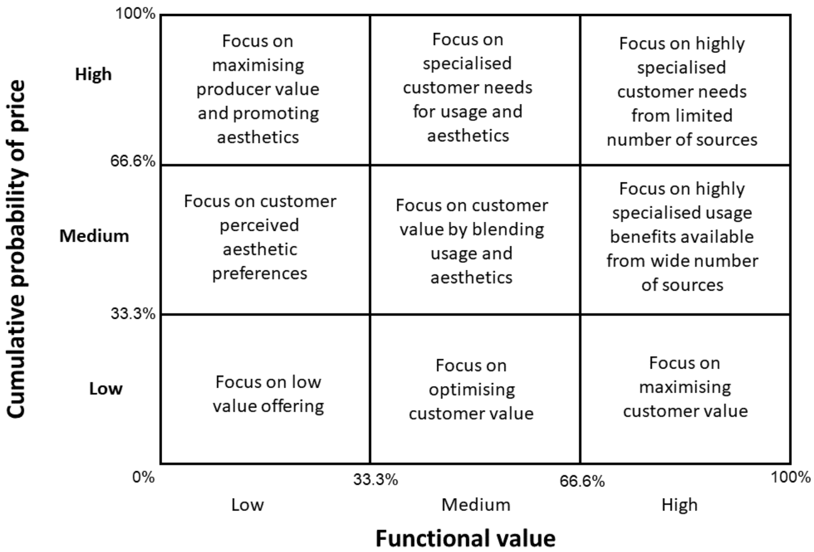
If on the other hand the cumulative probability of the price is held constant (e.g., only consider the row for mean price which has a cumulative probability of 50%) and change the functional value (i.e., from left to right) then value rises from 2% to 200% as a solution would have more functionality customers value for the same price.

This new approach, only to be used to compare similar complex systems, enables co-creation dialogues between customers and producers where the formula helps meaningful discussion and innovation with conversations amongst stakeholders focused on value. For example, in the extraction of oil and gas from shale plays does directional drilling or multiple slant wells offer best value to the project? This could be determined as shown in the example above.

This new approach called "Value, Functionality, and Price" (VFP) combines ideas of value, functionality, and price in a way that helps complex technological projects comprising customers and different vendors:

iii) Value ratio = Functional value / cumulative probability of price

In an attempt to make this of more practical use, a matrix is shown below that outlines what various scores of a Value Ratio imply (see matrix 1).



Matrix 1. The focus of a particular Value Ratio

9. Conclusions

This paper has addressed a core challenge in value engineering in that its practice is founded on an idea that mixes measurable and immeasurable concepts.

By overcoming this difficulty this paper links to a longer-term ambition to use AI as a form of recommendation system.

The paper is also of immediate benefit to VE practitioners as they can now distinguish between functionality that needs cost reduction and functionality that needs value enhancement. This should help the VE community to overturn views that all VE is useful for is cost reduction, as well as open doors to a stronger identification with augmenting customer value.

Today's VE practitioners can use this new approach named Value-Function-Price (VFP) with subsequent incremental invention in a workshop and look to the Value Ratio to judge if the suggested improvement really does bring more value forward. This enables VE to engage in co-creation activities where designers and customers collaborate in the act of invention. Matrix 1 offers the means for these two stakeholder groups (i.e. manufacturers and customers) to reflect on what each are trying to achieve.

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